



OVERDESIGN IN BUILDING SERVICES: THE HIDDEN ENERGY USE

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Abstract

This paper categorises and describes the various types of margins that are applied during building services design, and highlights the various stakeholders involved, from the early specification of requirements, through to the engineering design specification and installation. Using a case study of a hospital boiler upgrade, the paper differentiates between margins built into the regulatory, clinical, and contractual requirements, and the margins applied through the engineering design choices that allow for various contingencies and uncertainties. To meet energy targets, hospitals invest in products that use less energy. Whilst such interventions, such as lighting upgrades and control improvements provide some efficiencies, over-design of core systems often negate the savings. The over-specification and over-design of building service systems often results from the cumulative addition of various design margins. It is quite possible that sometimes margins are added as a matter of habit with no real thought as to whether they are really applicable to a particular situation, calling into question the issue of design procedures.

Keywords: Communication, Decision making, Case study, Human behaviour in design, Design margins

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1 INTRODUCTION

Reducing energy consumption is a statutory requirement and cost reduction measure for hospitals. To meet energy targets, hospitals invest in products that use less energy. However many of the building service systems that consume energy are over specified and over designed, generating design margins over and above the necessary requirements. This paper looks at design margins within building services engineering design from the perspective of both the literature and current industry practice, covering the magnitude of margins applied and the reasons for their use. The over-specification and over-design of building service systems often results from the cumulative addition of various design margins. To meet statutory energy and carbon reduction targets hospital technical staff and estates departments adopt costly interventions. Whilst such interventions, such as lighting upgrades and control improvements provide some efficiency benefits, these are often negated by the significant over-design of core systems such as steam and hot water services, cooling and ventilation systems. As highlighted in previous research (de Neufville et al., 2004; Peeters et al., 2008; Djunaedy et al., 2011) there is tendency towards over-capacity design of energy and engineering infrastructure to mitigate risk, which impacts on the ability of these systems to operate at their optimum efficiency point.

The paper categorises and describes the various types of margins (an overarching term that is used to describe the multiple contingencies added during the design process) that are applied, and highlights the various stakeholders involved, from the early specification of requirements, through to the engineering design specification and installation. Using a case study of a hospital boiler upgrade, the paper differentiates between margins built into the regulatory, clinical, and contractual requirements, and the margins applied through the engineering design choices that allow for various contingencies such as uncertainties in the initial design assumptions (rules of thumb) and building performance, safety margins that mitigate against risk, margins to meet a clients future expansion 'future proofing', and margins that to allow for the inevitable deterioration of a systems performance, due to natural wear-and-tear. The heuristic approach to energy infrastructure engineering design can lead to significant oversizing, above 25% additional capacity (Djunaedy et al., 2011). The excess cost associated with oversizing of energy infrastructure ranges from 10-33% (Peeters et al., 2008; Djunaedy et al., 2011).

2 LITERATURE REVIEW

The issue of margins that lead to the oversizing of building services is not unique to hospitals, but extends to all other commercial buildings. Margins have also been recognised as a significant issue in optimising engineering products.

2.1 Design considerations and the application of margins

Decisions to add surpluses above the requirements, which are applied at all levels during the design process, either on individual components or whole systems can be grouped under the catch-all category of 'design margins'. A useful definition is: "the extent to which a parameter value exceeds what it needs to meet its functional requirements regardless of the motivation for which the margin was included" (Eckert et al., 2013), which are added by different stakeholders for a variety of reasons. Design margins are often defined at the beginning of project design to provide flexibility; flexibility itself being defined as providing "functionality, performance, and capacity" each of which "consists of many attributes, which can also be thought of as requirements" (Banerjee and de Weck, 2004). Ross et al. (2008) describe the influences that might occur for a system to require modification, "change agents", and the potential outcomes of design decision-making. In earlier research papers, the need to understand and specifically design in margins, particularly when considering longevity in design, also looked at the categorisation of different approaches to the challenge (de Neufville et al., 2004; Saleh et al., 2009).

Consideration of future external trends is unlikely to be the responsibility of the design engineer and more probably undertaken by strategic decision-makers, who create initial specifications that meet financial, lifespan and return-on-investment (ROI) type, non-technical parameters. One paper goes so far as to say that the "analysis of markets and customer usage is neither in the engineers' job descriptions nor in their training" (de Neufville et al., 2004). Furthermore, recent research from a user-centred design perspective, acknowledges the need "to embrace the experience of a wider body of stakeholders" and how the education and training for the design and management team must improve "to fulfill social,

environmental and economic requirements” (Clements-Croome, 2013). De Neufville et al. (2004) describe how “traditional engineering typically manages risk through fixed specifications”, negating the need for designers to consider “probabilistic analysis” and thereby ensuring protection “from responsibility if their structure fails” (de Neufville et al., 2004). This idea of designing systems to fixed parameters is a common theme within research papers; “usually the range of expected behaviour is fixed in specification” (Banerjee and de Weck, 2004). Bacon also determines “that building energy performance directly relates to the engineers assumptions based upon occupancy levels, which are often standardised, leading to over-engineered systems for maximum occupancy levels” (Bacon, 2014). Further research determines “The widespread use of simple sizing tools – “previous experience” and rules-of-thumb – could be an indication of why oversizing is so prevalent” (Djunaedy et al., 2011). In some cases “many decisions are made at detail level, with limited consideration of overall solutions and overall performance/cost ratio” (Almefelt et al., 2005). Decisions are made throughout the design process considering how products will act in future; this can include their compatibility with other technologies, how easily future changes can be applied all within a potential framework of investment decision-making, such as ROI (Saleh et al., 2009). This is balanced by a need to ensure the design is correct for now, ensuring products are competitive and resource efficient, fitting within limited specifications. The Climate Change Act 2008 currently provides a legal necessity to properly ensure that building services infrastructure will be at the optimum conditions for efficiency. Bacon states that there is a “need for a fundamental change in... the engineering design process” (Bacon, 2014). He also cites various government and professional organisation reports suggesting a new approach to building design, utilising new innovations and techniques, is needed to effectively deliver lower energy consuming buildings (Bacon, 2014). Part of this reduction in energy use will be managed within the existing building stock using data driven techniques, such as Building Management Systems (BMS), currently utilised in many NHS Trusts (Jones and Eckert, 2016).

It is likely, given the current economic position of the NHS, that much of the building stock will require on-going upgrading and improvement, involving significant design engineering input. This is echoed in some design margin paper findings, albeit he approaches this from a different angle, arguing that “conventional design practice grossly over-estimates occupancy”, which therefore adds significant energy load to a building (Bacon, 2014). This oversight has been flagged previously in a paper which states “uncertainty and inefficiency in systems’ operation and use can readily develop through lack of attention to detail for occupants’ requirements” (Bordass and Leaman, 1997).

2.2 Risk and uncertainties

Operational risks and uncertainties associated with the design of the energy infrastructure and building service systems within hospitals can have significant and wide ranging consequences. As such, the concept of safe fail is frequently adopted, whereby safety and service shall be retained even if parts of the system or perhaps the whole system fails (Möller and Hansson, 2008).

2.2.1 Reliability – redundancy, segregation and diversity

Some of the most significant margins applied within building services design are to ensure reliability. The majority of hospital building service systems are designed to continue to operate in the event of partial or full system failure, this sustained resilience is achieved through the implementation of one of three closely related design principles; redundancy, segregation and diversity; these are seen as applications of the safe-fail principle. Reliability is the key concept here, and the latter three principals may be seen as means of achieving this (International Atomic Energy Agency, 1986), this is particularly important in a case of a hospital, as even the partial failure of a building services system such as heating boiler or ventilation plant fault serving an operating theatre or other critical area, could result in serious clinical consequences. The concept of segregation works on the basis that total system failure is more likely if its component parts are located physically too close to one another (Möller and Hansson, 2008), for example, the common proximity of two electric control panels, one serving run and the other serving standby heating pumps, if affected by a common flood or fire, could result in the total loss of that system. The related concept of diversity provides resilience on the basis that different system types are used to provide a common function (Möller and Hansson, 2008), for example the generation of cooling water from centralized refrigeration plant may be backed up by localised refrigeration systems to prevent loss of cooling capacity, in the event of a common component failure. Whilst both segregation and diversity are used in hospitals, hence forming part of the later discussion of this paper, the application of

redundancy within hospital building services design is by far the most frequently used method to safeguard against risk. The concept of redundancy relates to the provision of additional capacity in a system so that system performance is maintained despite partial system failure (Chen and Crilly, 2014), thereby an important means of achieving reliability. Having additional boilers than is necessary to meet the site maximum demand is an example of system redundancy, an example that provides key discussion points and the practical research contribution of this paper.

3 METHODOLOGY

The issue of hospital engineering systems overdesign within the context of this paper originated from wider PhD research looking at strategic energy management in Hospital Trusts. The first author has over 30 years' experience of working in energy management. Section 4 analyses the margins proposed by the Chartered Institute of Building Service Engineers (CIBSE) to allow for safety risks as well as other factors contributing to overdesign with an analysis of the reasons and mitigating factors.

The case study research was undertaken as semi-structured interviews with a range of decision-makers across the hierarchy of the hospital Trust, between February and September 2015. The interviews were conducted in a semi-structured style allowing the interviewees to explain how and what influences their ability to implement energy reduction measures within the organisation. Ensuring participants' anonymity also provided space for them to talk frankly, particularly where organisational constraints were perceived to negatively affect the decision-making process. Nine interviews were conducted initially, whereby general discussions regarding the hospital's 'strategic energy management' practices opened up further conversations regarding concerns over an inefficient, overcapacity boiler design which had been specifically upgraded to meet the requirements of a new private finance initiative (PFI) building, contract specification (the Private Finance Initiative (PFI) is a way of funding public infrastructure projects with private capital). Specific question sets were prepared for each interviewee, dependant on job role and responsibilities. The questions were arranged to provide a logical order and natural transition, and covered a wide range of topic areas, including; job roles, organisational governance, building and energy infrastructure, decision making, data use, reporting processes, energy budgeting and perceived barriers to energy efficiency. As the boiler house example grew in significance, a further two interviews were organised; one with a Trust-side project engineer directly involved in the boiler design scheme and another, with an experienced building services design consultant. Again bespoke question sets were prepared, covering; timelines, documentation, decision processes, capacity increases and project management specifically relating to the boiler upgrade scheme.

Table 1. List of relevant interviewees, in chronological order

Interview no.	Job Title	Date	Duration	Interviewer
P1	Deputy Director for Corporate Services	12/02/2015	48 minutes	DJ, CE
P3	Estates Operation Manager	12/02/2015	63 minutes	DJ, CE
P4	Energy Manager	12/02/2015	54 minutes	DJ, CE
P8	Estates Development Manager	20/04/2015	34 minutes	DJ
P10	Senior Project Manager	16/09/2015	20 minutes	DJ
P11	Chartered Building Services Design Engineer	28/09/2015	45 minutes	DJ

Table 1 lists interviews where conversations specifically arose relating to the boiler design project. The remaining five non-technical interviews P2, P5, P6, P7 and P9 are excluded from this table. All interviews were conducted face-to-face, recorded via a Philips Voice Tracer, converted to MP3, and transcribed into Microsoft word documents. Interview transcripts were analysed, initially by marking-up and annotating transcript documents. Once common themes had been identified from the first pass review, 'key word' searches were then undertaken via the Microsoft Word search bar to capture all comments relating to each common theme. Lists of quotations relating to each theme were then ordered into groups. The interview with the external design consultant was facilitated via a telecom call; notes were taken, capturing the salient points discussed. The interviews provided a useful overview of the decision processes specific to the boiler-house design, highlighting key influences over the design specification, limitations in technical knowledge and a general acceptance of the boiler over-capacity. Due to the long time lapse between project completion and the research interviews, external consultants

and other key people involved in the boiler design were unable to be contacted for the research. Therefore, some gaps should be presumed to exist within the overall picture of the project development.

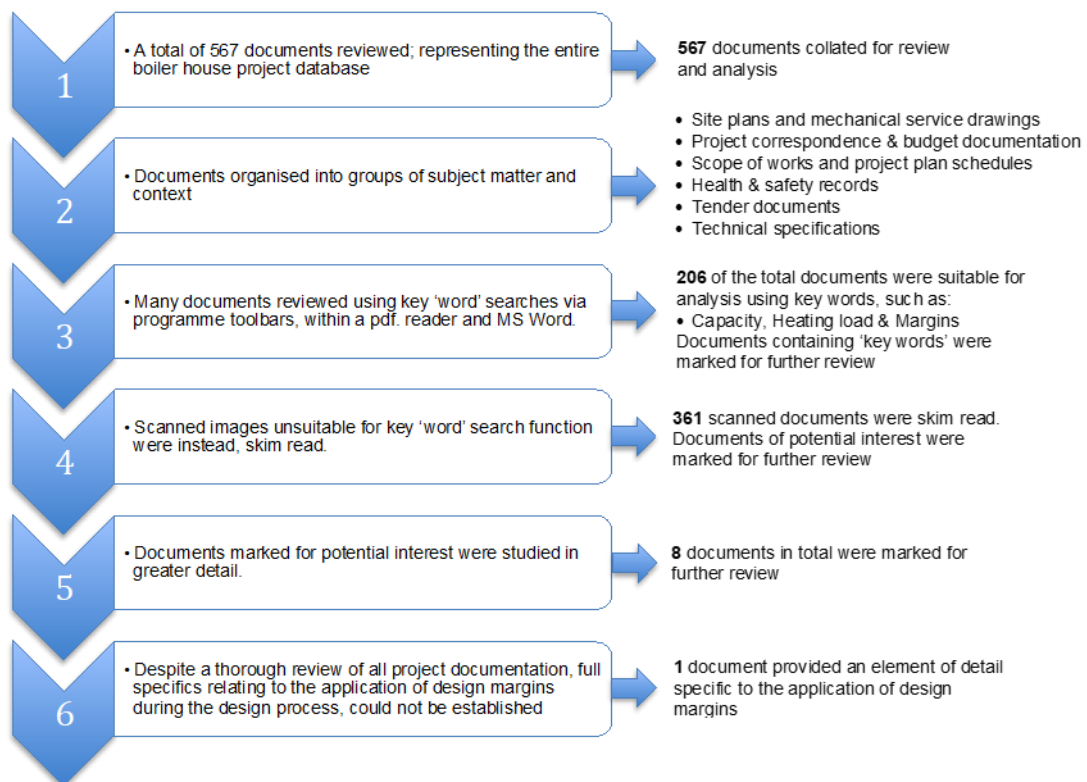


Figure 1. Procedure and analysis of document review specific to the boiler design

In addition to the research interviews, a document review was undertaken; details of the procedure and analysis of the document review is provided in Figure 1. In the author's capacity as an independent energy consultant to the Trust, full access to project documentation was provided. The focus of the document review was to establish what factors during the design process had led to the over sizing of the boiler plant, and the margins that had been applied. A total of 567 documents were reviewed, these were understood to represent the entire project database. The review was carried out using key 'word' searches (e.g. capacity, heating load, kWh) via programme toolbars, within a pdf. reader and Microsoft Word. A large proportion of the documents were scanned images, and so not compatible with the search function; these documents were instead, skim read. Where areas of potential interest were identified, text was studied in greater detail.

Despite this thorough review, project documentation did not allow the author to specifically determine the different margins, and where these were applied during the specification and design process.

4 MARGINS IN BUILDING SERVICE GUIDELINES

The literature describes three broad types of margin categories; intrinsic margins that form part of the calculation procedure, extrinsic margins that are added post-calculation (e.g. a deliberate addition to the building-heating load of 20%) and hidden margins that can be defined as an increase to a design parameter resulting from the use of inaccurate or unreliable data, e.g. selecting the 'next size up' when selecting an item of equipment (CIBSE, 1998; Opus, 1996). In addition to the practical reasons given above, design margins are also applied for less exact reasons, such as "to keep the client happy" or to avoid the risk of litigation (CIBSE, 1998).

The Chartered Institute of Building Service Engineers (CIBSE, 1986) suggests that margins are applied for a variety of reasons at different stages during the design process, to safeguard against uncertainty and risk. However, as these risks do not apply at the same time, the guidelines can lead to significant overdesign as a margin is added for each risk rather than an aggregate margin for all of the risks. Typical engineering margins (relevant to engineering parameters only) applied during the design of heating systems range between 5-25% across various margin parameters such as heat losses, heat transmitters,

boilers and distribution pumps etc. (CIBSE, 1998). They are added either during manual calculation or by default when using a software design package. Other margin categories applied during the design and installation process, are done so for a variety of reasons. Margins that allow for uncertainties within the initial design and data assumptions – within client specifications, may be necessary (e.g. assumptions relating to future demand, occupant numbers etc.). A range of safety and precautionary margins may also be added for numerous reasons (e.g. to allow for equipment power surges on start up or excess pressure on piped systems), but also to provide an element of flexibility during commissioning which allows for variations in system and equipment performance, and to provide reliability and resilience due to operational ‘wear-and-tear’, over time. Consequential margins such as installers uplift – “next size up’ may also be applied due to limitations associated with the availability or production of optimum sized equipment. A review of boiler sizes amongst a selection of manufacturers shows that choosing the next size up can account for a margin of about 15% typically (Opus, 1996). From the review and analysis of various industry publications, each of these individual margin categories can represent a margin uplift that ranges from 5-25% (CIBSE, 1986, 1998, 2006). Figure 2 which has been based on a mix of empirical evidence, industry publications and professional practice, provides an overview of margins typically applied during the specification, design and installation phases of a hospital building services project, together with a model of technical, psychological and organisational influence and mitigating initiatives.

The Issues	Margin Categories Applied	Influencing and Resultant Factors			Mitigating Initiatives
		Technical	Psychological	Organisational	
Over Specification ↓	<ul style="list-style-type: none"> Safety and risk margins Initial design and data assumption contingency Redundancy and resilience margins Future proofing - margins that allow for change management 	<ul style="list-style-type: none"> Fear of failure Ensure required performance is met To ensure resilience Additional safety factors 	<ul style="list-style-type: none"> 'Rule of thumb' estimates Uncertainty over occupancy Cognitive bias - custom & practise Bounded rationality - limited data upon which to make decisions Personal requirements - overzealous clinicians 	<ul style="list-style-type: none"> Future demand and organisational strategy Local policy requirements Time constraints Risk strategy Fear of Litigation Organisational governance Increased capital costs 	<ul style="list-style-type: none"> Improved data collection Clear strategic vision Collaborative working and knowledge share amongst project stakeholders Peer review by experienced consultant Value management Risk assessment
Engineering Over Design ↓	<ul style="list-style-type: none"> Safety and risk margins Engineering margins Performance variation margins Margins to offset equipment wear and tear Redundancy and resilience margins 	<ul style="list-style-type: none"> Fear of failure Allow for change Safety allowances Building regulations Additional resilience Uncertainties in building/plant performance 	<ul style="list-style-type: none"> Design engineers - knowledge and experience Uncertainties within initial specification Uncertainties within calculation methods Design engineer attitude and motives Considerations in respect to part load analysis Over cautious designer 	<ul style="list-style-type: none"> Safety requirements Redundancy requirements Health Technical Memorandum BREEAM requirements 	<ul style="list-style-type: none"> Value Engineering Calculation checks QA procedures Peer review by experienced design engineer Specification/final design comparison - requirements analysis Design management systems
Over Installation ↓	<ul style="list-style-type: none"> Safety and risk margins Installer margins - 'next size up' Engineering margins Performance margins for commissioning flexibility 	<ul style="list-style-type: none"> Equipment upsizing Over complicated controls Increased complexity Availability of materials and equipment Physical installation limitations 	<ul style="list-style-type: none"> Installer skills, aptitude experience and expertise Installer custom & practise Time constraints for installation - short cuts Behavioural constraints - quality compromised by convenience 	<ul style="list-style-type: none"> Selection of installation contractor Installation specification and project brief Additional post design changes - client variations 	<ul style="list-style-type: none"> Quality control Training and education Site supervision and productivity incentives Effective time management Effective project management
Over Sized & Over Complex Plant ↓ Poor Energy Performance	<ul style="list-style-type: none"> Multiplier effect - total cumulative design margin 	<ul style="list-style-type: none"> Inefficient part-load operation Sub-optimum plant operation Increased maintenance requirements Time constraints with regard to commissioning Difficult to repair and maintain due to technical complexity 	<ul style="list-style-type: none"> Reluctance to acquire knowledge of new and complex technologies resulting in lack of understanding and demotivation Reduced access and maintainability due to space restrictions - maintenance frustrations Reliance on specialist external contractors - additional management requirements 	<ul style="list-style-type: none"> Increased energy consumption Increased maintenance and replacement cost Inability to meet carbon reduction targets Building users may not be building owners - user/investor dilemma 	<ul style="list-style-type: none"> Re-commissioning - post occupancy evaluation Optimised control Improved monitoring and targeting Site energy audits Spend to save initiatives Post project review - lessons learnt database Feedback Retrospective technologies

Figure 2. Accumulation of design margins and influences, leading to over sized plant

Table 2 provides a simple example using the maximum margin percentage values that has been accumulated from text within various CIBSE publications (CIBSE, 1986, 1998, 2006), and a nominal base capacity of 100 units, to illustrate how the accumulation of margins can result in a significant capacity increase to 313 units, a 213% increase over and above the base requirement. It is therefore apparent that where a number of individual margins are applied in isolation during the design process, the multiplier effect of these often results in a large total margin that is unlikely to represent the risk.

Table 2. Example illustrating the impact of cumulative margins on capacity

Applied margins	% Margin applied	Cumulative capacity
Base capacity requirement	-	100
Initial design and data assumptions	20%	120
Engineering Calculations	25%	150
Installers uplift – ‘next size up’	15%	173
Building construction and integrity	10%	190
System and equipment performance	20%	228
Safety and commissioning margins	25%	285
Maintenance related margins	10%	313

5 CASE STUDY EXAMPLE – THE ROYAL STOKE UNIVERSITY HOSPITAL

5.1 The context of NHS hospitals

This research is carried out in the context of the National Health Service (NHS), the UK state run and state funded health provision that serves 93% of the UK population, represents 3-5% of UK carbon emissions, when including hospitals and other estate, transport impact and pharmaceuticals (Wilkinson et al., 2007). A large, ageing estate and increasing energy intensity in healthcare interventions, particularly those in acute hospitals and emergency care, are a growing challenge in meeting legally-binding, carbon reduction targets. In 2009, the NHS, via their dedicated Sustainable Development Unit, pledged to adhere to the 2008 UK Climate Change Act (i.e. a reduction in emissions of 80% by 2050 based on a 1990 baseline, supported by reductions of 34% by 2020 and 50% by 2025). In 2012, the carbon footprint of the NHS was calculated to be 25 million tonnes of carbon dioxide and equivalent greenhouse gasses or MtCO₂e (NHS Sustainable Development Unit 2013). Despite this significant carbon footprint there is limited evidence that energy reduction projects are undertaken as a priority within the healthcare setting (Short and Al-Mayaih, 2009; Short et al., 2012; Lomas et al., 2012; Bacon, 2014).

5.2 Research Overview

The key research of this paper focuses on the main low temperature hot water (LTHW) boilers that generate hot water to a district-heating network supplying various buildings across the Royal Stoke University site, with space heating and domestic hot water (DHW). The large over-specification of the boiler house currently running at four times the capacity needs of the Trust, is worth examining from a design margins perspective. In particular, the case study showed problems relate to the engineering design and the Trust’s inability to influence the design capacity, although attempts were made to modify the PFI contract specification. It is arguable, based on this boiler design example, which is supported by other studies (Peeters et al., 2008; Djunaedy et al., 2011; Bacon 2014), that the application of some design margins need to be challenged.

5.3 Specifics to the oversizing of the Royal Stoke University hospital boilers

Coal fired boilers were originally used to provide space heating and domestic hot water at the Royal Stoke University Hospital site, these were subsequently converted to natural gas. Despite conversion to gas, the 30-year old boilers were replaced during the late 1990’s. During 1998-99 a new energy centre was built on the hospital site, in a different location to that of the original boiler-house. In order to meet the thermal requirements of a new PFI development, the energy centre then had to be upgraded, something that Trust side engineering staff didn’t agree with, as it already “seemed to be rather over dimensioned, having three, 4 megawatt (MW) hot water boilers (Interview - P3).

From the detailed review of 567 boiler project related documents, just a single paper entitled ‘Energy Centre Report’ dated 20th December 2006 was found to provide some evidence as to the boiler sizing rationale. The report provided details of the heating load requirement for the PFI development, stating a total heat load of 9,513kW was necessary. This had been based on outline design calculations that included an additional 8% increase, to account for heat distribution losses. No engineering calculations or decision process notes were provided in support of these figures. The report also made clear that no heat load allowance had been made for the site retained estate, nor the Trust owned maternity and

oncology new-builds. From interview transcripts (P3, P4, & P10), it is understood that the final boiler capacity requirement specified by the PFI project team for the ‘PFI development’ only, was 12 MW. Despite the Trust engineering team challenging this at the time, the PFI project team were unwilling to compromise. Trust Management sought advice regarding the practical risks associated with not meeting their contractual obligation. Key concerns were not providing enough heat to the PFI installation and financial penalties imposed on the Trust resulting from the delay of the PFI programme. As a result, the 4 MW boilers were removed, and replaced by three 8.2 MW boilers, having a total installed capacity of 24.6 MW. From discussions with Trust staff (Interviews – P1, P3, P4, P10) it is understood that total current peak thermal demand for the Royal Stoke Hospital site is between 5 and 6 MW during winter, including the old and new Trust retained buildings, and newly constructed PFI estate. A recent addition to the heating system is a combined heat and power (CHP) unit that provides a further 1.4MW thermal capacity to the site. The boiler house design was undertaken by an engineering consultancy, engaged by the Hospital Trust. In addition to the 12MW specified, a further N+1 redundancy factor was then applied by the boiler house design team (Interviews – P8 & P10). N+1 redundancy is a form of resilience that ensures system integrity in the event of component failure or during maintenance downtime (the redundancy of a single boiler [N] is substituted by a boiler of matched capacity [+1]). Taking into consideration the additional thermal requirement of Trust retained buildings, there is a consensus amongst those staff interviewed, that the boiler design sizing rationale was based on the fact that two, 8.2 MW boilers would adequately satisfy the anticipated thermal requirement of 16 MW (12 MW for the PFI building + 4 MW for trust retained buildings) and a third 8.2 MW boiler would provide a N+1 redundancy factor, should one of the two duty boilers fail. Figure 3 illustrates boiler infrastructure changes and associated timelines.

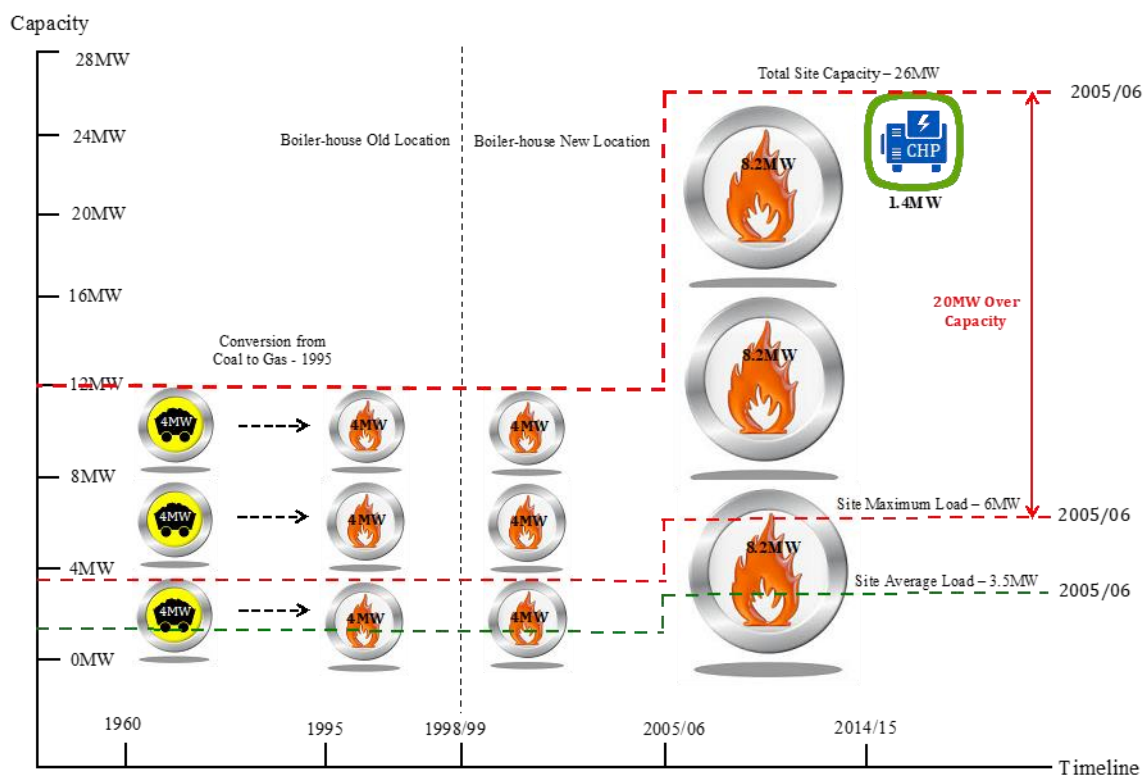


Figure 3. Boiler infrastructure changes and capacity increases over time

5.3.1 Boiler design stakeholders

As part of the 567 project document review, a Microsoft Excel spread-sheet was developed to capture and sort the various stakeholders involved in the design and installation process, and the timelines associated with their work input. From careful analysis of the data, it was established that 61 stakeholders were involved in this project over the course of a decade, stakeholders include; Trust side and PFI project teams, architects, M&E design consultants, equipment installers and commissioning engineers.

6 DISCUSSION, CONTRIBUTION AND FURTHER WORK

It is clear from the case study research of this paper, supported by other related literature, that there is a need to negate the cumulative impact of current design assumptions and margins. Whilst there is a need to apply margins to system designs to allow for uncertainties within; the initial design specification, building & system performance, calculation methods used, safety factors, future expansion, plant redundancy and maintenance, these margins should be clearly visible across all design and installation group stakeholders. Current practise, whereby a margin is added for each risk in favour of a single considered margin, covering all risks, can lead to significant overdesign. Design approaches from habit, custom and practice and the use of 'rules of thumb' are no longer acceptable.

It would appear from the case study research that the main factor leading to a four times over-capacity boiler system was due to the specification requested by the PFI project team, presumably based on assumptions relating to the new build development. Despite a thorough review of all project literature and in-depth conversations with the boiler upgrade senior project manager (Interview – P10) the rationale behind the specified capacity and what design margins had been applied, are not clear. Even fundamental questions such as, did the 12MW specification include, or exclude a redundancy factor, remain unanswered. Equally poignant is the fact that the initial boiler calculation was not challenged by strategic, non-technical decision-makers due to concerns over the systems ability to provide enough heat to the PFI installation and the prospect of huge financial penalties, should the project programme become delayed. Obviously this over-capacity has significant consequences on system operation and energy performance, impacting on the Trusts ability to meet statutory carbon reduction targets. Discussions with the energy manager also revealed that after a value engineering exercise, the burners fitted to the over-sized 8.2MW boilers have an inherently poor 'turndown' ratio. This renders them incapable of operating at an optimum point, particularly when considering the site average demand is just 3.5MW (Interview – P4). Clearly, full life-cycle costing had not been considered when making this design choice.

As the above comment relating to burner turndown suggests, there are ways to achieve better operational efficiency when plant and equipment is over-sized. Boilers can be fitted with efficient burners to provide greater turndown ratios. Circulation pumps, ventilation fans, chillers can all utilise variable speed drives together with well designed control strategies to ensure optimum modulation, based on building demand. That said, these retrofit technologies are expensive and will not be as effective, had the system been correctly sized in the first instance. Another alternative to overcome the issue of building services overdesign is to move away from redundancy strategies, used for back up, and engage the concept of diversity. A hospital example would be to install a localised heat-pump system that provides heating or cooling to an operating theatre in the event of routine maintenance or system failure, rather than doubling up on centralised heating and cooling systems. Margins should not be applied to a design unless there is a valid reason for their use. (When margins are considered necessary, better communication of the design margins applied and their reasoning are required to manage the overall effects, particularly for non-technical strategic decision-makers. Details relating to assumed building and system performance should also be recorded and communicated to project stakeholders. Future work may include the development of an industry-accepted checklist or quality assurance procedures that facilitate the capture of all design margins and assumptions, enabling these to be communicated to project stakeholders, from specification through to commissioning. A project review process that compares the intended design specification with post commissioning feedback may also provide a practical check of requirements, upon which lessons can be learnt and good practice can be established.

7 CONCLUSIONS

Both from a practitioners perspective and the academic literature there substantial evidence of the excessive application of design margins and consequent oversizing of building service systems, leading to its inefficient operation and energy performance. Design margins can be seen as part of the wider problem of over-engineering, coupled with design deficiencies and a lack of feedback to design (CIBSE, 1998). It is clear from the literature timelines cited within this paper that the excessive use of margins is not a new phenomenon, but an issue that has occurred for a number of decades. It is interesting to note that based on the primary research of this paper, that there appeared to be no identifiable reason for the oversized boiler system nor could explanations be remembered for the use of those particularly excessive margins. It is quite possible that sometimes margins are added as a matter of habit with no real thought

as to whether they are really applicable to a particular situation, calling into question the issue of design procedures. Buildings are still not delivering their expected performance; hence the key research message to be taken from this paper is that a clear client brief, a detailed design specification, transparency of margins applied and design assumptions made, effective communications between design teams, and good design (feedback will all contribute to reduced margins, effective design and efficient building performance).

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